OBSERVATIONAL EVIDENCE OF ACCRETION DISK-CAUSED JET PRECESSION IN GALACTIC NUCLEI

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ABSTRACT

We show that the observational data of extragalactic radio sources tend to support the theoretical relationship between the jet precession period and the optical luminosity of the sources, as predicted by the model in which an accretion disk causes the central black hole to precess.

Subject headings: accretion, accretion disks — black hole physics — galaxies: active — galaxies: jets

1. INTRODUCTION

An S-(or Z-) shaped morphological symmetry has been observed for many extragalactic radio sources, for example, for 39 of 365 extended radio sources collected by Florido, Battaner, & Sanchez-Saavedra (1990), for more than 30% of quasars with redshifts less than 1 and with a two-sided radio structure (Hutchings, Price, & Gower 1988). This phenomenon has generally been attributed to precession in the orientation of the radio jet. With precessing jet models, it is indeed possible to fit apparently more complex image maps of many extended radio sources (e.g. Gower et al. 1982). Jet precession was also invoked to account for other phenomena, such as the bending and misalignment of parsec scale jets in compact radio sources (e.g. Linfield 1981; Appl, Sol, & Vicente 1996), and the variability of either continuum or line emissions observed in active galactic nuclei (e.g. Rieger 2004; Caproni, Mosquera Cuesta, & Abraham 2004; but see §4).

Presumably, the jet material is ejected along the axis of a spinning black hole at the center of a galactic nucleus. There have been basically two models on what causes the central black hole to precess. Begelman, Blandford, & Rees (1980) first proposed that the precession of the black hole could be due to the existence of another hole in the same nucleus. Later, Lu (1990) suggested that a surrounding, titled accretion disk could also do the job, on the basis

of the model of Sarazin, Begelman, & Hatchett (1980) for the galactic object SS433. Both the models predicted that there should be a tendency for the brighter sources to present the shorter precession periods, but the predicted precession period – luminosity relations in the two models were quantitatively different (Roos 1988; Lu 1990). While the idea of binary black holes is indeed interesting and has been applied in recent years to a number of extragalactic sources with precessing jets (e.g. Lobanov & Roland 2005 and references therein), the scenario of a single black hole with an accretion disk surrounded seems to be simpler and more commonly applicable to active nuclei. In fact, the disk-caused jet precession model has received meaningful observational supports since it arose. For instance, Veilleux, Tully, & Bland-Hawthorn (1993) reported their detailed observational results of the Seyfert galaxy NGC 3516, and this source follows the theoretical precession period – luminosity relation of Lu (1990); Peck & Taylor (2001) revealed that the compact source 1946+708 has radio jets with a tilted, circumnuclear disk, and stated that such an observed morphology is consistent with the scenario of Lu (1990).

Most previous studies of jet precession in galactic nuclei were for individual sources. In this Letter we try to do the job in a more general sense. We first describe the model of jet precession caused by an accretion disk, which is an improvement of that proposed by Lu (1990); and then collect all extragalactic sources to date with needed observational data available to test our model.

2. THE MODEL

A spinning (Kerr) black hole has angular momentum $J_* = aGM^2/c$, where M is the black hole mass, and a is the dimensionless specific angular momentum, $0 < a \leqslant 1$. Consider an accretion disk surrounding the hole. The disk is tilted in the sense that its rotation axis is misaligned with that of the hole. A ring with width dr in the disk has angular momentum $dJ = 2\pi r^2 \Sigma v_\phi dr$, where Σ is the surface density of the disk, and v_ϕ is the rotational velocity of the disk material, so the angular momentum per logarithmic interval of radius is $J(r) = dJ/d(\ln r) = 2\pi r^3 \Sigma v_\phi$. There exists a critical radius r_p in the disk defined by $J(r_p) = J_*$. Due to the Lense-Thirring effect, disk material interior to r_p will be aligned with the equatorial plane of the black hole, while the outer portion of the disk ($r \gtrsim r_p$) with sufficiently large angular momentum will maintain its orientation, and will cause the central hole along with the inner disk to precess (Bardeen & Petterson 1975). Some material of the inner disk is assumed to be ejected out along the hole's spin axis, forming a precessing jet.

The precession rate of the central black hole and the inner disk is equal to $2GJ(r)/c^2r^3$ (Sarazin et al. 1980). Since only regions $r \gtrsim r_p$ in the disk contribute to this precession

and $J(r)/r^3$ decreases as r increases, the fastest precession rate Ω is produced by the ring at $r = r_p$ with $J(r) = J_*$, i.e. $\Omega = 2GJ_*/c^2r_p^3$. Introducing the mass accretion rate $\dot{M} = 2\pi r\Sigma v_r$, where v_r is the radial inflow velocity of the disk material, Ω can be expressed as

$$\Omega = (2/M)(G/a)^{1/2}(\dot{M}v_\phi/cv_r)^{3/2}. \tag{1}$$

The best known model of accretion disks is that of Shakura & Sunyaev (1973), in which v_ϕ is Keplerian, $v_\phi = (GM/r)^{1/2}$, and for the outer region of the disk $v_r = 10^{5.73}\alpha^{4/5}m^{-1/5}\dot{m}^{3/10}r_*^{-1/4}f^{-7/10}\mathrm{cm\ s^{-1}}$, where α is the dimensionless viscosity parameter, $m = M/M_\odot$, $\dot{m} = \dot{M}/\dot{M}_{\rm crit}$, with $\dot{M}_{\rm crit}$ being the critical accretion rate corresponding to the Eddington luminosity, $r_* = r/r_g$, with $r_g = 2GM/c^2$ being the gravitational radius, and $f = 1 - (3/r_*)^{1/2} \approx 1$ (Kato, Fukue, & Mineshige 1998, p. 88). Substituting the expressions of v_ϕ and v_r into equation (1), the precession period $P(\equiv 2\pi/\Omega)$ can be calculated numerically,

$$P = 10^{9.25}\alpha^{48/35}a^{5/7}(M/10^8M_\odot)^{1/7}(\dot{M}/10^{-2}M_\odot\ \mathrm{yr}^{-1})^{-6/5}\mathrm{yr}. \tag{2}$$

The mass accretion rate $\dot{M}$ is related to the luminosity of the source L as $L = \eta\dot{M}c^2$, with η being the efficiency of energy conversion. Note that here L should be the optical luminosity of the galactic nucleus, rather than the radio luminosity of the jet, because the jet material is likely to derive its energy from the spinning black hole or from the disk via electro-magnetic processes, the jet luminosity does not reflect directly the accretion rate. By using the definition $\log(L/L_\odot) = 0.4(5.71 - M_{\rm abs})$, where $M_{\rm abs}$ is the absolute magnitude of the nucleus in the B band, and 5.71 is M_B of the sun, a relationship between P and $M_{\rm abs}$ is obtained finally,

$$\log P(\mathrm{yr}) = 0.48M_{\rm abs} + 20.06 + \frac{48}{35}\log\alpha + \frac{5}{7}\log a + \frac{1}{7}\log(\frac{M}{10^8M_\odot}) + \frac{6}{5}\log\eta. \tag{3}$$

This equation improves significantly equation (5) of Lu (1990), which is $\log P(\mathrm{yr}) = 0.6M_{\rm abs}+$ const., as not only the slope 0.6 has been recalculated to be 0.48, but also the previously unclear constant in the formula has been explicitly expressed.

The critical radius r_p in the disk can be calculated as

$$\begin{aligned} r_p &= (J_*v_r/\dot{M}v_\phi)^{1/2} \\ &= 10^{17.22}(\alpha/0.1)^{16/35}a^{4/7}(M/10^8M_\odot)^{5/7}(\dot{M}/10^{-2}M_\odot\ yr^{-1})^{-2/5}\mathrm{cm}, \end{aligned} \tag{4}$$

which is about several thousand times of the black hole's gravitational radius r_g . A similar result for r_p has been obtained in the model for accretion disks in active galactic nuclei given by Collin-Souffrin & Dumont (1990).

3. OBSERVATIONAL TESTS

The theoretical $P - M_{\rm abs}$ relationship of equation (3) is practically testable, as P and $M_{\rm abs}$ are observational quantities, and the ranges of values of the four parameters are all known, namely $\alpha \sim 0.001 - 1$, $0 < a \leqslant 1$, $M \sim 10^6 - 10^{10} M_\odot$, and $\eta \sim 0.1$. As mentioned in §1, many extragalactic radio sources show phenomena which are suggestive of jet precession. Unfortunately, for most of those sources no precession periods have been measured, the number of sources with both the jet precession period and the nucleus magnitude data available is still rather small. We collect from the literature 41 such sources to our knowledge, and list them in Table 1. The following comments are in order. Concerning the precession period, it is usually too long to be observed directly. The best way known to evaluate this period for a source is by fitting its (S-shaped or apparently more complex) radio map with a precessing jet model, like what was done by Gower et al. (1982). This is indeed the case for most sources listed in Table 1. Not surprisingly, the precession period obtained this way is by no means definite and accurate, it should be regarded as estimation of the order of magnitude only. For a few cases (3C 196, 3C 305, M 84, and OJ 287) the method of map fitting could not be (or has not yet been) used, the precession period was estimated by some other arguments. As to the sources' optical absolute magnitudes, they are in general quite inaccurate and inhomogeneous in the literature. For most of our collected sources we have made use of the LEDA Database and the SIMBAD Database, where the M_B values can either be found directly or be calculated from given visual magnitudes m_B and redshifts z. We have made corrections so that all magnitudes in Table 1 are in the B band, and with $H_0 = 50$ km s^{-1}Mpc^{-1}, $q_0 = 0$.

With all these uncertainties in mind, it seems that the data in Table 1 tend to support an inverse correlation between the jet precession period and the optical luminosity of the galactic nucleus as equation (3) predicted, i.e. the brighter the nucleus is, the faster the jet precesses, as shown more clearly in Figure 1. For a quantitative comparison, we draw in the figure the theoretical $P - M_{\rm abs}$ correlation of equation (3) by three straight lines. The middle solid line corresponds to the most typical values of the four constant parameters, i.e. $\alpha = 0.1$, $a = 0.8$, $M = 10^8 M_\odot$, and $\eta = 0.1$. This line fits the observational data quite well. The upper and the lower dashed lines are also for $\eta = 0.1$, but for larger values $\alpha = 1$, $a = 1$, and $M = 10^{10} M_\odot$; and smaller values $\alpha = 0.003, a = 0.5$, and $M = 10^6 M_\odot$,

respectively. It is seen that all the 41 sources are located within the region bounded by these two reasonable limit lines. Thus at this point the observational data are in good agreement with the theoretical prediction of the model.

4. DISCUSSION

Precession cone opening angle. Another physical component of the jet precession model is the half-opening angle ψ of the precession cone along which the black hole's spin axis rotates. Unlike the precession period P, ψ has not been calculated and predicted theoretically in our model, nor in the binary black hole model. The only system in which ψ is known ($\sim 20°$) by observations is the galactic object SS433. For extragalactic sources, the only way known to evaluate ψ is by fitting a precessing jet model to the observed morphology and kinematics of the jet. In this fitting, ψ is deduced as a free parameter along with others such as the precession period, viewing angle, and speed of the jet (e.g. the early work Gower et al. 1982 that ignored the physical cause of jet precession, and the most recent one Lobanov & Roland 2005 that adopted the binary black hole model). Table 1 lists values of ψ available in the literature, all obtained this way. For the inner disk with angular momentum much smaller than that of the black hole, one can expect that the hole's spin axis almost coincides with the total angular momentum vector along which both the hole and the disk precess, i.e. the hole's precession cone opening angle is very small (or the hole even does not precess at all). But for the case we consider here, the outer disk has angular momentum comparable to or larger than that of the hole, and gas accretion is likely to occur at random angles, thus initially the two angular momentum vectors can make any angle, i.e. ψ can be of any value. In a very recent paper, King et al. (2005; most clearly Figure 1 there) showed that, whatever the initial angle between the two angular momentum vectors (the hole's and the disk's) is, the hole suffers a torque which always acts to align the hole's spin with the total angular momentum, i.e. ψ is always made to decrease with time. It is seen from Table 1 that the values of ψ are indeed random, and 20 of the total 33 values there are relatively small ($1° - 16°$). A small ψ could be a feature of the initial configuration of a source, or it could be a result of evolution from a larger initial ψ due to the alignment torque.

Some insight about ψ may be gained from the study of a test particle orbiting a black hole. The off-equatorial plane motion of a test particle is characterized by the Carter constant Q. To very high accuracy, Q can be treated as the square of the particle's specific (per unit mass) angular momentum projected into the equatorial plane (perpendicular to the hole's spin). The inclination angle i of the particle's circular orbit is defined as $\cos i = L_z/(L_z^2 + Q)^{1/2}$, where L_z is the particle's specific angular momentum parallel to the hole's spin (Hughes

& Blandford 2003). For large r, Hughes (2001) gave a formula (in $G = c = 1$ units): $(L_z^2 + Q)^{1/2} = (rM)^{1/2}[1 - 3a(M/r)^{3/2}\cos i]$. It is seen that depending on the values of two constants L_z and Q, i can be of any value (note that i corresponds to 2ψ in our model since we consider a ring with angular momentum J equal to that of the hole J_*), and that whatever the value of i is, the particle's whole specific angular momentum $(L_z^2 + Q)^{1/2}$ approaches the Keplerian value $(rM)^{1/2}$ as r increases.

Short term precession? As seen from equation (2), the jet precession period is generally very long in our disk-caused precession model. Appl et al. (1996) have also shown that the typical precession period of a supermassive black hole caused by a tilted massive torus is of the order of 10^6 years. Therefore we include in Table 1 only those sources with precession periods ranging from $\sim 10^3$ to $\sim 10^8$ years. We notice that for a number of extragalactic sources the periodicity of about 10 years in the light curves has been observed, and this phenomenon has also been attributed by some authors to precession of jets and/or accretion disks (e.g. Caproni et al. 2004). In our opinion, such a short periodicity is most likely not related to the precession. It is due to either flaring activity in the disk, or geometry and non-linear motion of the jet. At least in some cases, setting such a short precession period has led to unrealistic results in the model fitting. For example, Caproni & Abraham (2004) assumed the period of 10.1 years observed in the B-band light curve of 3C 345 to be the jet precession period, and claimed that 3C 345 has two black holes with masses of $\sim 4 \times 10^9 M_\odot$ and an orbital separation $\leq 7.3 \times 10^{16}$ cm. Such a separation is smaller than $60r_g$, then there would be no room for a stable accretion disk to exist at all! This is of course not to argue against the binary black hole model itself. Also applying the binary black hole model to 3C 345, Lobanov & Roland (2005) obtained a precession period of 2570 years, black hole masses of $7.1 \times 10^8 M_\odot$, and an orbital separation $\sim 10^{18}$cm in their model fitting, and these parameters seem to be more reasonable. Similar problems may exist for objects 3C 120, 3C 273, and OJ 287, for which precession with periods ~ 10 years was also assumed (see Table 1 of Caproni et al. 2004), while more plausible precession periods have been deduced by other authors (Table 1 here).

Summary. The observational evidence is likely to be in favor of the disk-caused jet precession model according to the data in Table 1, at least at a statistical level, but it is still far from reaching a definite conclusion in the following senses. First, except that it does not require binary supermassive black holes to present in a large number of active nuclei, our model does not offer an explanation of the observational data which is conceptually different from that offered by the binary black hole model. Some sources, namely 1928+738, OJ 287, Mrk 501, PKS 0420-014, and 3C 345, though being included in Table 1 to support our model, were studied by corresponding authors in the framework of binary black hole model. Second, that the black hole's precession cone angle can be of any value should be

regarded as a hypothesis. In particular, it is not clear whether this angle as large as several tens degrees is physically possible. Further investigations addressing this specific question on a fundamental basis are required. Third, reasons for a large scale misalignment between the accretion disk and the black hole are also unclear. The misalignment may be created through gas accretion which is driven for example by minor mergers of galaxies with satellite galaxies and is likely to occur at random angles, then it is still a problem whether and how this misalignment can be preserved over timescales long enough to be reconciled with the extent of kpc-scale jets showing clear signs of precession.

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Table 1. Extragalactic sources with jet precession period P, half-opening angle of precession cone ψ, and optical magnitude $M_{\rm abs}$ data available

Object	P(yr)	ψ (degrees)	Ref.[a]	$-M_{\rm abs}$	Ref.[b]
3C 196	10^6	—	(1)	26.4	(34,35)
3C 305	$5\ 10^6$	—	(1)	22.8	(34)
3C 273	$\sim 10^3$	$1 \sim 2$	(2)	27	(34)
3C 129	$9.2\ 10^6$	12	(3)	23.3	(34)
3C 315	$\sim 10^7$	$<17 \pm 15$	(4)	22.6	(34)
3C 388	$5\ 10^5$	6 (to 12)	(4)	23.2	(34)
NGC 326	10^6	$< 23 \pm 3$	(4)	23.3	(34)
4C 18.68(2305+18)	$4\ 10^4$	$< 80 \pm 6$	(4)	24.6	(34,35)
1315+347	$9\ 10^3$	$< 25 \pm 4$	(4)	25.4	(35)
1730-130	$5\ 10^4$	$(<)$ 35	(4)	27	(34,35)
0945+408	$1.6\ 10^4$	23 ± 11	(4)	26.9	(34,36)
0224+671	$3\ 10^4$	14 (to 34)	(4)	23.1	(35)
0716+714	$\sim 10^5$	35 ± 8	(4)	25.9	(35)
0707+476	$\sim 10^5$	$(<)$ 4	(4)	26.6	(37)
3C 449	$1.1\ 10^5$	$\leqslant 16$	(5)	21.3	(34)
1857+566	10^4	5	(6)	27.3	(34,35)
4C 29.47	$6\ 10^6$	60 ± 10	(7)	21.9	(34)
2300-189	$3.4\ 10^6$	69 ± 5	(8)	21.8	(34)
3C 418	$\sim 5\ 10^4$	$\sim$70	(9)	29.1	(34,35)
3C 120	$5\ 10^4$	9	(10)	22.9	(34)
NGC 6251	$1.8\ 10^6$	8	(11)	22.5	(34)
4CT74.17.1	$9\ 10^5$	10	(12)	24.4	(38)
3C 138	8200	1	(13)	24.7	(34,36)
Hydra A (3C 218)	$3\ 10^5$	—	(14)	23.8	(34)
4C 41.17	$3\ 10^6$	—	(15)	25.7	(39)
3C 119	$2\ 10^3$ or $6\ 10^4$	3 or 17.5	(16)	26.4	(34,35)
1928+738	$4\ 10^5$	$8 \sim 10$	(17)	26.3	(34,36)
NGC 3516	$\sim 10^7$	60	(18)	21.6	(34)
B2 0828+32	$2\ 10^8$	25	(19,20)	20.7	(34)
NGC 3079	$1.2\ 10^6$	—	(21)	22.1	(34)
3C 390.3	$4\ 10^5$	—	(22)	21.2	(34)

Table 1—Continued

Object	P(yr)	ψ (degrees)	Ref.[a]	$-M_{\rm abs}$	Ref.[b]
1243+036	$3.6\ 10^5$	—	(23)	25.4	(39)
OJ 287	$7\ 10^4$	3.4	(24)	25.5	(37)
0153+744	880	10	(25)	29.4	(37)
NGC 5128(Cen A)	$\sim 10^7$	—	(26)	23	(34,36)
M 84(NGC 4374)	$\sim 10^7$	10–15	(27)	21.6	(34)
Mrk 501(1652+398)	$\sim 10^4$	< 12	(28,29)	23.5	(34)
NGC 4258	$2.5\ 10^5$	several tens	(30)	21.8	(34)
PKS 0420-014	$\sim 10^4$	~ 12	(31)	27.3	(34,35)
3C 345	2570	1.45	(32)	27.1	(34,35)
PKS 2153-69	$1.8\ 10^6$	11.6	(33)	21.9	(34)

[a] References for P and ψ ; [b] References for $M_{\rm abs}$.

References. — (1) Lonsdale & Morison 1980; (2) Linfield 1981; (3) Icke 1981; (4) Gower et al. 1982; (5) Gower & Hutchings 1982; (6) Saikia et al. 1983; (7) Condon & Mitchell 1984; (8) Hunstead et al. 1984; (9) Muxlow et al. 1984; (10) Benson et al. 1984; (11) Jones et al. 1986; (12) Roos & Meurs 1987; (13) Fanti et al. 1989; (14) Taylor et al. 1990; (15) Chambers et al. 1990; (16) Nan et al. 1991; (17) Hummel et al. 1992; (18) Veilleux et al. 1993; (19) Klein et al. 1995; (20) Parma et al.1985; (21) Baan & Irwin 1995; (22) Gaskell 1996; (23) van Ojik et al. 1996; (24) Vicente et al. 1996; (25) Hummel et al. 1997; (26) Israel 1998; (27) Quillen & Bower 1999; (28) Rieger & Mannheim 2000; (29) Conway & Wrobel 1995; (30) Cecil et al. 2000; (31) Britzen et al. 2001; (32) Lobanov & Roland 2005; (33) Young et al. 2005; (34) LEDA Database; (35) SIMBAD Database; (36) NASA/IPAC Extragalactic Database; (37) Véron-Cetty & Véron 2003; (38) Wirth et al. 1982; (39) van Breugel et al. 1998.

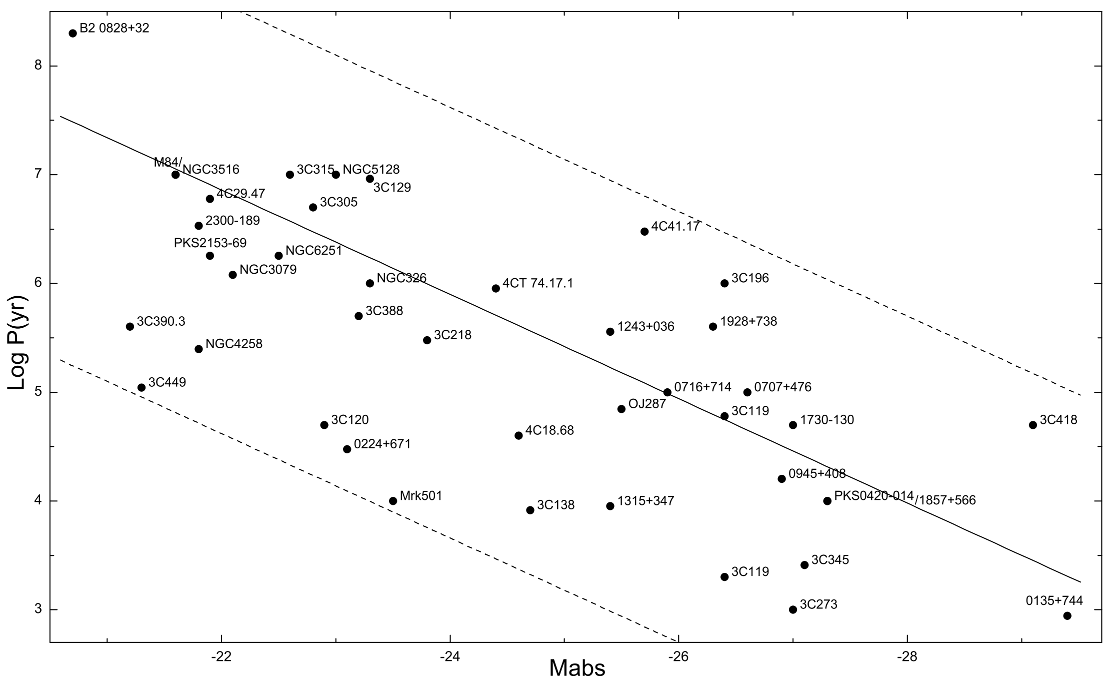

Fig. 1.— Precession periods P vs. optical absolute magnitudes $M_{\rm abs}$ for 41 extragalactic sources listed in Table 1. Three straight lines draw the theoretical prediction equation (3), the upper, middle, and lower ones are for parameters $(\alpha, a, M/M_{\odot}, \eta)$ equal to $(1, 1, 10^{10}, 0.1), (0.1, 0.8, 10^8, 0.1)$, and $(0.003, 0.5, 10^6, 0.1)$, respectively.